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Methods for predicting seabed scour around marine current turbine

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ABSTRACT

Marine energy sources are able to make significant contributions to future energy demands. Marine current has huge potential to supply renewable energy as compared to the other energy sources. Marine environment is harsh for the installation and operation of marine current turbine (MCT). Seabed scour around marine current turbine is induced when the flow suppression occurs at the seabed. Seabed scour is widely recognised as a difficult engineering problem which is likely to cause structural instability. The study found that the previous works mainly focus on the bridge piers, wind turbines and ship propeller jets induced scour. Little information to date was found to predict the MCT induced scour. The current paper proposes the potential equations to predict the MCT induced scour. The study also recommends the consideration of the rotor into the existing equations for future research.

Contents

1. Introduction

The installation of marine structures leads to the changes of flow patterns around the structures. The contraction of flow commonly occurs when the flow passes through a narrow area of structure. The formation of horseshoe vortex can happen in front of a monopile structure, whereas the formation of lee-wake vortices (with or without vortex shedding) can happen behind a structure. The generations of turbulence, wave reflection, wave diffraction and wave breaking are associated with flow passing through a marine structure. These flow phenomena cause the instability and liquefaction of soil leading to excessive sediment transport and seabed scour [1,2].

The impact of a marine structure to seabed is an essential environmental study at the planning stage for an engineering project [3]. The interaction between the flow and structures may

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cause scouring at the seabed leading to the structural instability [4–6]. Marine current turbine (MCT) is a rotating device designed to harness the kinetic energy of marine current and generate electricity. It consists of a number of blades connected to a supporting structure and it either rotates about a horizontal axis or vertical axis [7]. The installation of a monopile structure for marine current turbine gives no different effects from other offshore structures. The presence of MCT structure changes the flow pattern. The flow contraction accelerates the flow in its vicinity and leads to the local scour around the structure [8,9].

Climate change is one of the most challenging problems that humans have to deal with in the 21st century [10]. Most countries such as those in the European Union (EU) start to increase the electricity generation from renewables as part of their climate strategy [11]. Each renewable source has its own positive and negative attributes such as availability, affordability and environmental impacts [12]. The electricity generation from marine current sources is more predictable compared to the other renewables such as solar power and wind energy [13]. Marine current resource is therefore a vital natural resource to harness in order to secure the cleaner future energy supply [7]. Structural safety due to the seabed scour is one of the main considerations to take into account when considering the applicability of marine current renewables.

The foundation of MCT should be protected in order to prevent failure due to seabed scouring. The consequence of foundation failure may lead to the collapse of the entire MCT. The inclusion of a protection unit to prevent seabed scouring is important at the initial stage of design. The cost involved for scour and scour protection is considered as one of the highest contributors to the total cost of the entire offshore project. For instance, the cost of foundation for wind turbine can be up to 30% of the total cost when the scour protection is included [1].

The study of scour for marine current turbine is important to make marine current energy to be economically viable. The scour study can be started by understanding the previous studies on other marine structures such as piers and piles. The fundamental theories of scour are well-documented in the books of Whitehouse's "Scour at Marine Structures" [6] and Sumer and Fredsøe's "The Mechanics of Scour in the Marine Environment" [4]. The flow pattern and the scour process around the piers and piles have been previously investigated by using analytical methods, experimental tests and numerical modelling [1]. However, the study on mechanics of scour and scour protection method for marine current turbine has not been thoroughly studied. Little information to date was found to discuss the protection of the foundation of MCT. The engineering equations have not been summarised to provide a simple tool to investigate the seabed scour of MCT. The current study uses the experiences of induced scour due to wind turbines, ship's propeller jets and bridge piers as references for the scour study of MCT.

2. Seabed scour for support structures

2.1. Support structures of marine current turbine

Marine current turbine is generally divided into horizontal axis marine current turbine and vertical axis marine current turbine [14]. The technological development of the horizontal type does seem more mature compared to the vertical type due to its high promised performance. The established commercial turbines of Seaflow and SeaGen are both horizontal axis marine current turbines. The development of marine current technologies includes the design of an effective support structure to hold the turbines safely. The support structure for horizontal axis turbine can be categorised into four main types as shown in Fig. 1 [7]:

(1) Gravity structure: The gravity structure is a concrete or steel structure to hold the turbine by its self-weight to resist overturning.
(2) Monopile structure: The monopile structure is a large steel beam with a hollow section penetrating to a depth of seabed between 20 and 30 m for a soft seabed. The processes of predrilling, positioning and grouting are required for the seabed condition of hard rock.
(3) Tripod/piled Jacket structure: The tripod Jacket structure anchors each corner of the basement to the seabed by using steel piles. These steel piles are driven in between 10 and 20 m into the seabed to hold the structure firmly. Tripod Jacket structure is a well-established technology in the application of oil and gas industry.
(4) Floating structure: Floating structure is suitable for the application of deep water. The floating device appears at the surface of the water to hold the submerged turbine structure in the water. The submerged structure is locked to the mounting device at the seabed by using chains, wire or synthetic rope.

2.2. Seabed scour

Rambabu et al. [16] stated the fluid flow, geometry of foundation and seabed conditions are the governing factors for the seabed scouring. The characteristics of fluid flow include the current velocity, Reynolds number of model and Froude number of flow. The abovementioned four types of foundations have different areas of contact to the seabed. The selection of support structures lead to different flow patterns occurring at the foundation with different formation of flow-induced vortices in the vicinity of support structures. Different scouring patterns are induced by different geometry of foundation.

The gravity structure is most susceptible to seabed scouring due to its large contact area with the seabed compared to the other three types of foundation. The determination of geometry size and seabed preparation is required in order to implement the gravity structure as the foundation of MCT. The scour of monopile is less susceptible compared to gravity structure due to its low contact area with the seabed [7]. The scour development of piled jacket structure is more complicated compared to the aforementioned due to its footing shape [17]. McDougal and Sulisz [18] stated the floating structure gives lowest impact on the seabed scour due to the low area of contact between the structure base

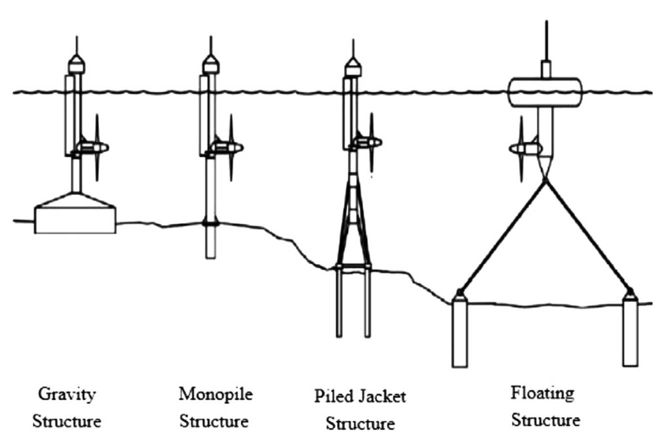

Fig. 1. Different types of support structures with horizontal marine current turbines [15].

and seabed. However, it may have less advantage on the positioning of the turbine in harsh marine environment.

The seabed preparation is time consuming and the construction process of the foundation is costly. The potential sites for marine current energy have normally fast flowing fluid, which may be dangerous for divers. Gravity structure may be suitable to the sites without excessive seabed preparation. Monopile structure can be used to replace the gravity structure as no seabed preparation is required prior to the installation [7]. The piled Jacket and floating structures are both alternatives without seabed preparation. The floating structure needs solid points at seabed, fixing the structure to the seabed through chains.

The scour development around monopile structures has been studied extensively for the foundation of offshore wind turbine in the past few decades [1,17]. The application of monopile structures in MCT is suggested for both the cost and structural stability [15]. The first tidal turbine in the world (300 kW Seaflow) is supported by a monopile, which generated electricity successfully [19]. The monopile structure is analogous to the bridge piers and piles which have been studied for more than a hundred years. The knowledge of the bridge piers and piles study is transferable to the monopile structures of MCT. There is some information in the existing knowledge pool, which can be used to study scour of MCT.

Whitehouse [20] developed a conceptual model of scour sensitivity which includes the full range of marine sediment types as well as liquefaction risk of sediments under extreme wave event. This indicates how scour might be expected to develop under normal and extreme conditions. This conceptual model could be a preliminary reference to assess the scour around MCT. Besides that, Whitehouse [6] demonstrated a clear flowchart to assess the potential scour problem around a structure. This flowchart is slightly modified and transferable to the scour of MCT and it can be treated as an analytical tool to study the scour issue around the support structures of MCT. The critical parameters are shown in Fig. 2. According to the flowchart, the governing factors such as wave period, current speed, and sediment type are converted to physical features initially and followed by carrying out calculation or measurements. The likelihood of scour around MCT has been determined theoretically at last.

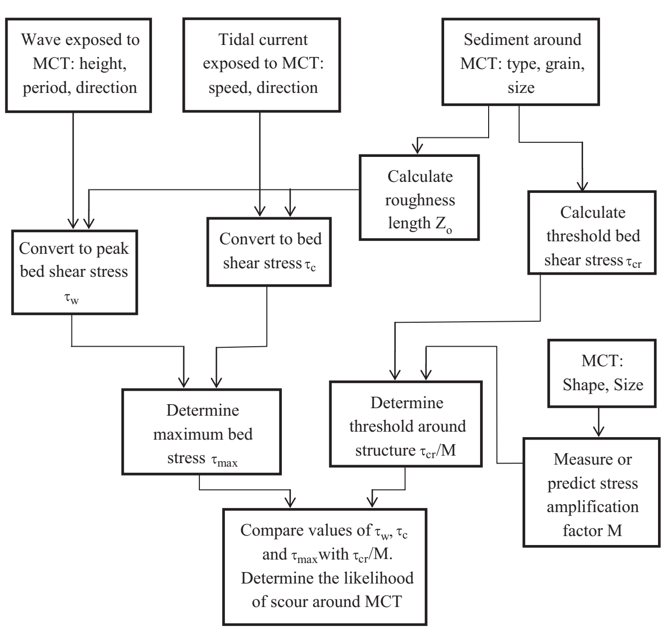

Fig. 2. Flow chart for assessing the possibility of scour around marine current turbine.

No field measurement of MCT's scour was found to date based on the initial study. The scour data from offshore wind farm was used as initial benchmark for the study of MCT's scour. Whitehouse et al. [3] assessed the scour condition of several offshore wind turbine farms with monopile structures. The data of water depth, wave and current condition were collected for each site. The field measurement was made after 6 months of installation. The deepest scour was 1.47D_{pile} (pile diameter 1.5 m) in the current-dominated sandy environment according to Whitehouse et al. [3]. The offshore wind turbine was installed in a site with strong tidal current (peak current speed at 1.4 m/s) and also sheltered from waves. A wider range of offshore wind turbines have been assessed to further include the different scour conditions. Whitehouse et al. [3] concluded that scour of monopile at wind farm is a progressive process. The scour development depends on a range of tidal, seasonal and longer term variations in currents, wave action and the water depth at the foundation.

3. Empirical equations for scour prediction of pile/pier

Numerous equations have been proposed to estimate the scour depth of a pier or pile in the previous studies, as shown in Table 1. Neill [21] proposed a simple equation in 1973 to relate the depth of scour to the diameter of penetrated structure to be a constant (K_s). K_s is the correction factor of pier shape, which is a constant depending on the shape of penetrated structure. Neill [21] proposed the correction factor $K_s=1.5$ for round-nose pier or circular pier and $K_s=2.0$ for rectangular pier. The study of Neill has been the foundation for the works of Richardson et al. [22] from Colorado State University (CSU), Breusers et al. [23,24], Breusers and Raudkivi [25], Ansari and Qadar [27] and Richardson and Davis [28]. These researchers included more parameters to consider the incoming flow, water depth, bed condition and size of sediment to enhance Neill's equation.

Richardson et al. [22] from Colorado State University (CSU) improved Neill's equation by considering the water depth and incoming flow. The angle attack of incoming flow and the water depth are both being considered in Richardson's equation. Richardson's equation proposed that the ratio of the depth of scour to the diameter of pier is two times of the multiplication of four dimensionless terms. These dimensionless terms are term of pier geometry, term of angle attack, term of water depth over diameter ratio and term of Froude number of flow.

Breusers et al. [23,24] improved the empirical equation for predicting the scour depth based on experimental observations with consideration of tidal flow in 1977. The bed conditions, size of bed sediment and water depth were included in Breusers's equation. The inclusion of the bed conditions and size of sediment is important to relate the source of scour (incoming flow) to the area being scoured (seabed). Breusers and Raudkivi [25] in 1991 included the consideration of the water depth (K_y) as Richardson's equation and the group of pier alignment (K_β). The correction factor of bed conditions proposed by Breusers et al. [23,24] in 1977 has been replaced by an analogous correction factor, namely sediment grading (K_σ). The correction factor of grading considers the seabed with various layers, which is vulnerable to be scoured, rather than only the top layer of bed. The consideration of sediment grading is essential at the seabed with non-uniform sediments.

Sumer et al. [26] carried out the experimental investigation on scour around piles exposed to waves. His research suggested that the effects of lee wake and horseshoe vortex are the two crucial components related to scour process. The horseshoe vortex contributes to the scour in front of the structure, whereas the lee wake forms the vortex shedding contributing the scour at the back of structure. The conditions of horseshoe vortex and lee wake depend

Table 1
Summary of equations for predicting scour around piles/piers.

Existing equations	Notation
Neill [21] $\frac{S}{D}=K_s$	S is the vertical distance between the maximum depth in scour hole in equilibrium situation and the surrounding undisturbed bed, D is pile diameter, and K_s is the correction factor of pier shape (Appendix A)
Richardson et al CSU $\frac{S}{D}=2.0K_sK_\theta\left(\frac{h}{D}\right)^{0.35}F_r^{0.43}$ $K_\theta=\left(\cos\ \theta+\frac{L}{a}\ \sin\ \theta\right)^{0.65}$ $F_r=\frac{U_c}{(gh)^{0.5}}$	K_θ is the correction factor for flow angle of attack (Appendix B), h is water depth, F_r is the Froude number of incoming flow, θ is angle of flow attack, L is pier length, a is pier width/diameter, U_c is depth-averaged current velocity and g is gravitational acceleration
Breusers et al. [23] $\frac{S}{D}=1.5K_sK_\theta K_bK_d\ \tan\ h\left(\frac{h}{D}\right)$ $K_b=0,\quad if\frac{U_c}{U_{cr}}<0.5$ $K_b=2\left(\frac{U_c}{U_{cr}}\right)-1,\quad if 0.5\leqslant\frac{U_c}{U_{cr}}<1$ $K_b=1,\quad if\frac{U_c}{U_{cr}}\geqslant 1$	K_b is the correction factor for bed condition (Appendix C), K_d is the correction factor for size of bed material (Appendix D), U_c is the depth-averaged current speed and U_{cr} is the threshold depth-averaged current speed
Breusers and Raudkivi [25] $\frac{S}{D}=2.3K_yK_sK_dK_\sigma K_\beta$	K_y is the correction factor of flow depth, K_d is the correction factor of pier and sediment size, K_σ is the correction factor of sediment grading and K_β is the correction factor of pier alignment
Sumer et al. [26] $\frac{S}{D}=1.3\{1-\exp\quad(-m(KC-6))\}$ $KC=\frac{U_mT}{D}$	m is an empirical factor determined from experiments as a constant of 0.03, KC is Keulegan–Carpenter number (drag force/inertia force of flow), U_m is amplitude of the wave velocity variations near the bed in absence of pile (statistic parameter), T stands for wave period of incoming flow in second
Ansari and Qadar [27] $\frac{S}{D}=0.86D^2\quad$ where $D<2.2m$ $\frac{S}{D}=3.06D^{-0.6}\quad$ where $D<2.2m$	D is projected width of pier
Richardson and Davis [28] $\frac{S}{D}=2.0K_sK_\theta K_bK_dK_W\left(\frac{h}{D}\right)^{0.35}F_r^{0.43}$	K_W is the enhance correction factor for pier width/pile diameter
Sumer and Fredsøe [4] $\frac{S}{D}=1.3\{1-\exp\quad(-A(KC-B))\}$ for $KC\geq B$ $A=0.03+\frac{3}{4}U_{CW}^{2.6}$ $B=6\exp(-4.7U_{cw})$ $U_{cw}=\frac{U_c}{U_c+U_m}$	U_c is the undisturbed current velocity, and U_m is the maximum value of the undisturbed orbital velocity at the sea bottom (statistic parameter)
Raaijmakers and Rudolph [31] $\frac{S}{D}=1.5K_vK_h\ \tan\ h\left(\frac{h}{D}\right)$ $K_h=\left(\frac{h_p}{h}\right)^{0.67}$ $K_w=1-\quad\exp(-A)$ $A=0.012KC+0.57KC^{1.77}U_c^{3.67}$	K_v is correction factor accounting for wave action, K_h is correction factor accounting for piles that do not extend over the entire water column, h_p is pile height and not over h

on the Keulegan–Carpenter (KC) number [26]. Sumer et al. [26] proposed KC number can be used to relate to the equilibrium scour depth on live beds. KC number is a ratio of amplitude of wave velocity variations and wave period of incoming flow to the diameter of a pile, as shown in Table 1.

Ansari and Qadar [27] estimated the ultimate depth of local scour at bridge piers based on his empirical study from field measurements. The equation is developed based on the curves of envelope from the field data with the consideration of a wide range of parameters. The scour depth is related to solely one parameter, which is the diameter of pier. The development of the equation may be transferable to produce the scour equation due to marine current energy. However, the sufficient scour data from MCT may be required for the development by using the approach of Ansari and Qadar.

Richardson and Davis [28] proposed an enhanced equation to determine the ultimate scour depth for both live-bed and clear-water scours in 2001. The equation considers the large particle as the sediment at seabed and the wide pier in the scour process. The large particle may reduce the scour depth at seabed compared to the small particle as sediment. For the consideration of wide piers, Richardson and Davis [28] conducted the flume studies to investigate the scour depth by using wide piers in shallow water. The results from experimental study are compared to the field measurement of the scour depth at bascule piers (a type of wide pier). The enhanced correction factor of pier width (K_W) is proposed in addition to the correction factor of pier shape (K_s) in 1975 to consider the impact of wide piers to the scour depth. The K_W can be applied when the following conditions are matched: (1) the ratio of flow depth (h) to pier width/pile diameter (D) is less than 0.8; (2) the ratio of pier

width to median diameter of bed material (d_{50}) is greater than 50; (3) the Froude number of flow is subcritical.

Sumer and Fredsøe [29] carried out the investigation to include the influences of current to the ocean wave induced-scour proposed in 1992. The equation is derived from the experiments in the range of KC in between 5 and 30 for live-bed condition. The tidal current changes with time in a day and therefore the orbital velocity (velocity of particles due to wave motion) is used for the equation derivation. The time-averaged velocity has been used to consider the current speed in the equation. Sumer and Fredsøe [29] also suggested that the depth of time-averaged current-induced scour is 1.3 times of the diameter of pile ($S/D=1.3$) with a standard deviation of 0.7. Other than that, den Boon et al. [30] proposed that the maximum depth of scour around a monopile with sole consideration of current is 1.75D when no protective unit is used at the seabed.

The prediction of scour depth for full water depth piles is well developed. All the aforementioned predictors are applicable to full water depth piles. However, if the pile height-to-diameter ratio is smaller than a critical value, the size of the horseshoe vortex in front of the pile will decrease with a decrease in pile height [4]. Therefore, the scour depth in front the cylinder will reduce with decrease in pile height. The decrease of pile height also weakens the vortex shedding behind the cylinder, which results in the reduction of scour depth behind the structure. More and more attention has been drawn to quantify the effect of pile height to scour depth. Raaijmakers and Rudolph [31] proposed an equilibrium scour depth equation with considerations of wave action and pile height lower than the water level in 2008. The equation is applicable in anyone of following conditions: (1) the KC number is low; (2) the height of pier is lower than the water depth; (3) the pile is relatively wide compared to the water depth. More recently, Simons et al. [32] presented experimental works on scour development around truncated cylindrical structures. Their results show that depth and extent of scour are largely reduced for the cylinder height less than one cylinder diameter compared to tests with a full water depth cylinder. Besides, their study demonstrated the scour depth with respect to tidal flow condition. The tests indicate that scour is remarkably reduced with bidirectional tidal condition compared the equivalent unidirectional current. The flow condition at potential MCT sites plays a crucial role for the scour around the support structure of MCT.

The previous studies demonstrated that the depth of scour for piers or piles is significantly influenced by the geometry of structure, condition of incoming flow, seabed condition, seabed material, and the water depth. These parameters will give the analogous impacts to the seabed scour for the monopile structures of MCT. The rotating rotor of MCT may influence the scour mechanism around the support structures, especially when the rotor is close to the seabed. The rotor of the MCT becomes an additional factor for the scour process. The well-established knowledge on the turbine wake and ship propeller jets could offer a deep insight on the hydrodynamics of flow disturbed by the rotor. The wake characteristics and ship propeller jets induced scour will be discussed in the following section.

4. Wake characteristics and ship propeller jets induced scour

4.1. Wake characteristics

The presence of rotor on monopile structure results in different hydrodynamic conditions compared to a single monopile installed in the marine environment. The fluids passing through the rotor plane region experience velocity reduction and form an expanding wake. The faster moving stream serves to re-energise the wake, breaking it up and increasing the velocity [33]. Myers and Bahaj [34] carried out wake studies on horizontal axis MCT and found that the flow field in the near wake region of MCT is dominated by the combined wake from both the support structure and rotor. The wake effect of turbine may alter hydrodynamics in the vicinity [35]. The increased turbulence in the wake of MCT could increase the shear stress imposed on the seabed [36]. The scour process around MCT is potentially to be affected by the interaction between sediments and wake.

Pinon et al. [37] conducted wake study of three-bladed horizontal axis MCT in uniform free upstream current. The axial velocity profiles at different locations behind the turbine have been illustrated in Fig. 3, where r is radial distance, R_t is radius of turbine, D_t is diameter of turbine, V_a is axial velocity, V_o is free stream velocity. The wake has approximately 50% velocity deficit in near wake region (1.2D behind). The wake is not fully covered even at 8.0D downstream. It has approximately 35% velocity deficit. The velocity deficit of wake decays as downstream distance increases. This is in line with observation reported by Myers et al. [38].

Myers and Bahaj [33] carried out another experimental analysis of the flow field around horizontal axis tidal turbines by using disk rotor simulators. They declared that varying disk proximity to seabed causes different mass flow below the rotors. It could results in the wake further persist downstream and slow down the wake recovery process. The lesser flow beneath the disks causes lesser flow mixing with the wake so that the rate of wake recovery is slower. The flow pattern underside of the wake and within the wake could be affected by the submerged depth of the disks. The tip clearance of turbine blades is critical in the scour process. Wang [39] claimed that turbine shaft should be kept one turbine diameter away from seabed to avoid severe sediment movement and disturbance of marine life near seabed. It further testifies the tip clearance playing an importance role in overall MCT system. We detected acceleration of fluids under the turbine blades in Pinon et al. [37] work. The study conducted by Sun [40] also claimed that there is localised flow acceleration under the energy extraction device. The acceleration of flow may influence the scour and deposition process around the support structures of MCT.

4.2. Ship propeller jets

Ship propeller has a reverse mechanism as marine current turbine with a number of similarities in hydrodynamic characteristics. Marine current turbine harnesses kinetic energy from the current flow [41] and a ship propeller converts the torque of a shaft to produce axial thrust for propulsion [41,42]. MCT produces the wake and the ship propeller produces the jets during operations, respectively.

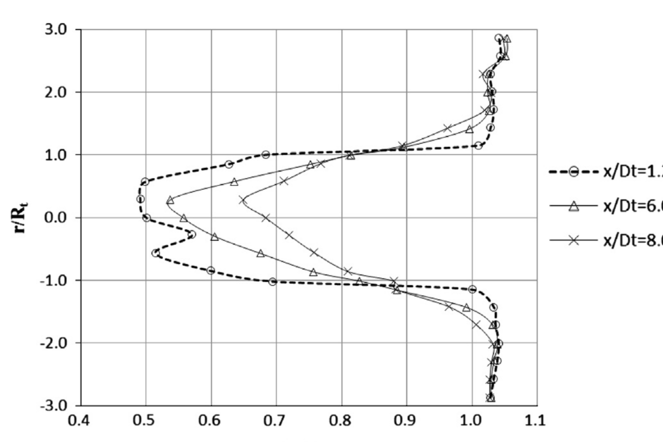

Fig. 3. Wake characteristics of marine current turbine [37].

Seabed scouring due to ship propeller jets has been highlighted by researchers including Sumer and Fredsøe [4], Whitehouse [6] and Gaythwaite [43]. These authors proposed the velocity prediction within a ship's propeller jet is the initial step to investigate the seabed scouring. Lam et al. [42] conducted laser Doppler anemometry (LDA) measurements and stated that the axial component of velocity is the main contributor to the velocity magnitude at the initial plane of a ship's propeller jet. The tangential and radial components are the second and third largest contributors to the velocity magnitude.

Lam et al. [44] presented fluids flow in the zone of flow establishment from a ship propeller. The measurements at two locations in the zone of flow establishment have been selected and demonstrated in Fig. 3, where R_p is radius of propeller, D_p is diameter of propeller, V_o is efflux velocity for ship propeller jets and free stream velocity for turbine wake. The axial velocity at $x/D_p=0.79$ and $x/D_p=1.05$ have little differences. It shows two-peaked ridges velocity profile with a low velocity core at the centre. The axial velocity distribution of turbine wake (1.2D) presented in Fig. 4 shows reverse velocity distribution as ship propeller jets. It has two dips of velocity deficit and a high core velocity near the centre. The axial velocity of turbine wake further downstream shows one dip only. The propeller and the turbine both have three blades. The diameter of the propeller (76 mm) is much smaller that of turbine (700 mm). The experiment conducted by Lam et al. [44] is in "bollard pull" condition (zero advance speed). The velocity outside the jets is zero which is different with the flow field outside the turbine wake. The velocity distribution of turbine wake ($x/D_t=1.2$) has been inverted in order to compare with that of ship propeller jets. The inverted axial velocity profile of turbine wake has similar pattern as the velocity distribution of ship propeller jets (see Fig. 3). It is foreseeable the velocity profile of ship propeller jets and inverted wake will be more identical if the propeller and turbine has similar geometrical characteristics. The well-established knowledge of ship propeller jets could be used as references for study the wake development of MCT.

A review of the equations used to predict the velocity distribution within a ship's propeller jet has been done by Lam et al. [45]. The review found that the rotational and radial components of velocity are still poorly understood compared to the axial component of velocity. The accuracy of the entire jet relies on the initial prediction of efflux velocity [45,46]. Efflux velocity is defined as the maximum velocity taken from a time-averaged velocity distribution along the initial propeller plane [47]. Equations for predicting efflux velocity have been proposed by Stewart [46], Hamill [48] and Hashmi [49], as shown in Table 2. These studies have found that the efflux velocity of propeller jets was associated with thrust coefficient (C_t), speed of rotation of propeller in revolutions per second (n) and propeller diameter (D). Stewart [46] reported that the coefficient used in the equation to predict efflux velocity was not a constant. This coefficient depends on the propeller characteristics. Hamill [50] carried out an extensive study to investigate seabed scour due to the propeller jet by using both the fine and coarse sands. The temporal development of maximum depth of scour has been examined and it can be written in a dimensional consideration, as shown in Table 2. Hamill [50] suggested that the scour depth relates to the densimetric Froude number, size of sediment and the clearance between the propeller and seabed. The maximum velocity and its distribution of a jet mainly depend on the characteristics of a turbine. The analogous consideration as ship propeller jets induced scour needs to be made for the scour prediction of MCT.

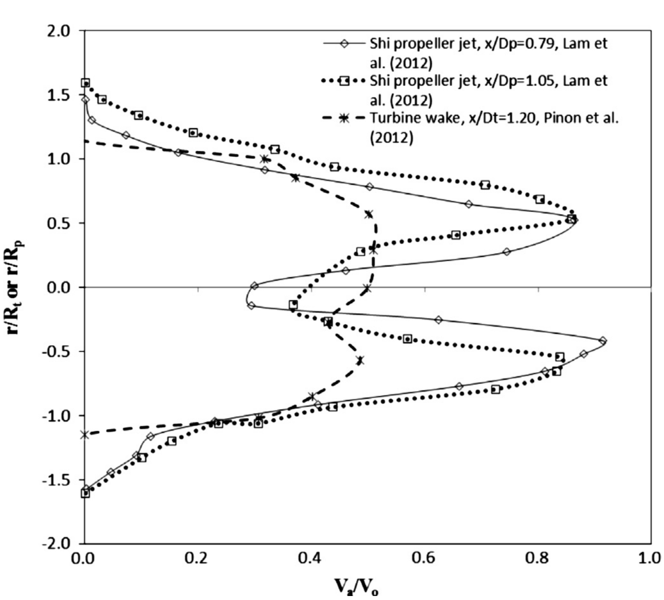

Fig. 4. Comparison of velocity profile between a ship propeller jet and turbine wake.

5. Scour around marine current turbine

5.1. Dimensional analysis

Dimensional analysis can be used to formulate the equation used to predict the scour around a MCT. Breusers et al. [24] proposed that the scour depth can be expressed in a relationship of S/D with other relevant factors. According to the current review, the functional relationship for scour depth normalised by the diameter of monopile of MCT can be related in Fig. 5.

5.2. Proposed equations

This paper aims to identify the appropriate approaches for predicting scour depth around a monopile structure of MCT from the existing knowledge. Empirical method is one of the solutions to predict the scour around MCT. Rudolph et al. [51] conducted a comparison between the existing empirical equations and the results from field study and concluded that the empirical equation from Breusers can be used to predict the scour depth effectively.

However, Breusers's equation does not include a Froude number in his expression. The inclusion of a Froude number is important as a determination of the nature of a flow [24]. Richardson and Davis [24] adopted Froude number in his expression. Even potential MCT sites have deep water the Froude number is quite small unlike in river. The free surface in proximity to rotor allows the water depth to vary and the consideration of gravity cannot be ignored. The extraction of energy from a flow results in channel head drop. The head drop for a single turbine unit in a large channel is quite small. The effects could be aggravated in MCT array farm. A row of MCTs cause significant change of water depth in the downstream as well as increase of flow speed. This subsequently results in pronounced variation of Froude number [52]. Breusers's, Richardson and Davis's equations have been selected as two of the proposed equations to develop an engineering model named scour time evolution predictor (STEP) to predict the development of scour evolution of offshore structures. In STEP, the comparison of these two empirical equations against experimental measurement has been made [24], as shown in Fig. 6.

In Fig. 6, the variation between the empirical equations and the experimental measurements can be found. Harris et al. [24] stated that the empirical scour depth predictors have a reasonable agreement with the experimental measurements. These empirical equations are a reasonable starting-point to develop a time-varying model, which includes the scour depth due to tide, wave and their combination. This scour time evolution model has been applied in

Table 2
Equations for efflux velocity and depth of scour.

Proposed equation	Notation
Hamill [48] $v_0 = 1.33nD\sqrt{C_t}$	$\boldsymbol{V_0}$ is efflux velocity, n is speed of rotation of propeller in revolutions per second, D is propeller diameter and C_t is thrust coefficient
Hamill [50] $\frac{\varepsilon_m}{D} = f\left[F_0, \frac{D}{d_{50}}, \frac{C}{d_{50}}\right]$ $F_0 = \frac{V_0}{\sqrt{gd_{50}\frac{\Delta\rho}{\rho}}}$	ε_m is maximum depth of scour, F_0 is densimetric Froude number, d_{50} is median sediment grain size, C is clearance between the propeller tip and the seabed, g is acceleration due to gravity, $\Delta\rho$ is difference between the mass density of the sediment and the fluid, and ρ is density of fluid
Stewart [46] $V_0 = \xi nD\sqrt{C_t}$ $\xi = D^{-0.0686}(P/D)^{1.519}BAR^{-0.323}$	$\boldsymbol{\xi}$ is Stewart's efflux coefficient, P/D is the pitch ratio of the propeller, BAR is the blade area ratio (ratio of projected area of all blades to the total area of the propeller disc)
Hashmi [49] $V_0 = E_0 nD\sqrt{C_t}$ $E_0 = (D/D_h)^{-0.403}C_t^{1.79}BAR^{0.744}$	$\boldsymbol{E_0}$ is Hashmi's efflux coefficient, D_h is the diameter of propeller hub

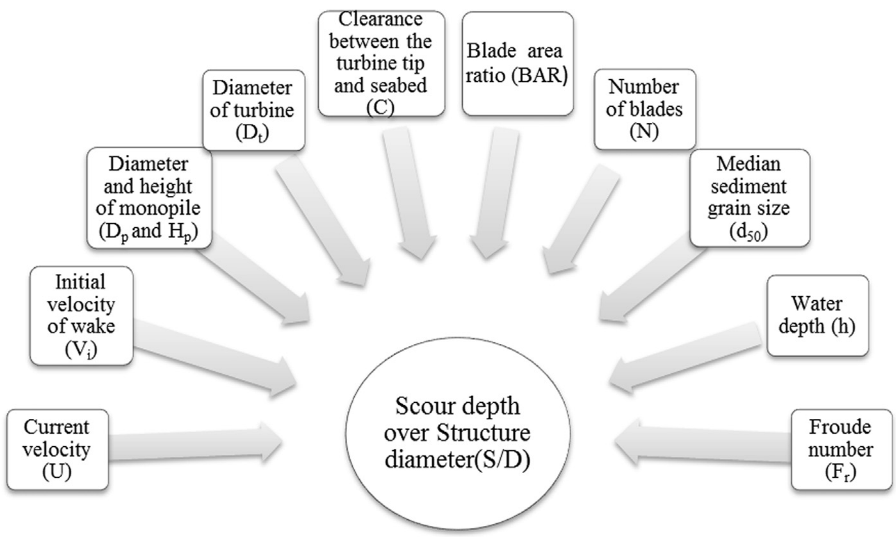

Fig. 5. Parameters relevant to marine current turbine induced scour.

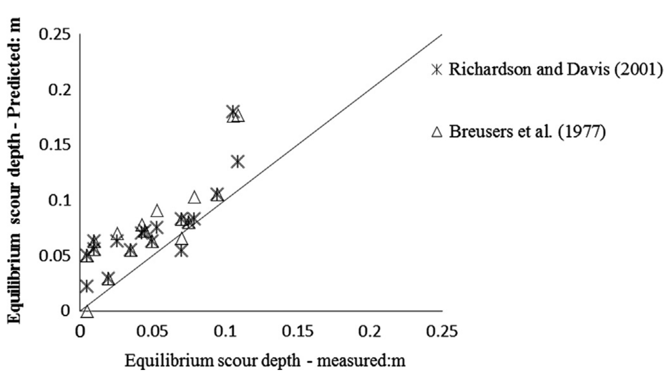

Fig. 6. The comparison of predicted scour depth with measured scour depth [24].

the offshore wind turbine studies and it may be able to be adopted for the scour prediction of MCT. Equations from Breusers, Richardson and Davis have great potential as the proposed equations to predict the scour depth of MCT.

Annandale [53] proposed an approach to estimate the potential erosion of complex soils by relating the stream power (river) to the soil resistance of scour. Harris et al. [54] applied Annandale's approach to the marine environment with modifications. Harris et al. [54] called this modified approach as Earth Materials approach, which can be used to assess the scour in complex marine soils. Harris's approach requires information of soil properties. The seabed is a formation of soil with different layers, which the depth of each layers need to be used as an input. The depth of each layers need to be obtained through site investigation. Richardson and Davis's equation has been adopted to calculate the maximum depth of scour in the Earth Materials approach.

Raaijmakers and Rudolph [31] proposed that the scour equation which is based on the extensive data from in-house experiments and published literatures. Their equation has also been compared to the results from numerical simulation. Both the experimental and numerical results show the validity of their equation in the scour prediction. This equation may be suitable for the prediction of MCT induced scour when the height of MCT support structure is lower than water depth. Further validation is required in order to identify the applicability of the equation for precise MCT scour prediction.

Additional factors need to be considered in the scour prediction of MCT based on the aforementioned equation. MCT has the special features of rotor, which may need to be taken into account. A seabed boundary layer is between the seabed and rotor tip height that will hit the foundation structure [55]. The rotor causes the acceleration of the bed velocity between the rotor and seabed.

The suppression of flow occurs to increase the stresses exerted on the seabed and consequently leads to the seabed scouring. The clearance between rotor and seabed becomes critical in the investigation of the MCT scour. The flow suppression occurs on the ship's propeller jets induced scour, which may be transferable to the study of MCT induced scour.

If the clearance between the rotor and seabed is relatively high, the flow suppression at seabed becomes insignificant. The consideration of rotor on the seabed scouring is therefore negligible. Although the rotors are significant to cause flow suppression, the equations from Breusers, Richardson and Davis are still the best equations to date according to author's literature review. It has been widely applied in offshore engineering. No information to date was found to quantify the influence of rotors to MCT induced scour. The future works are recommended to identify these influences. The conventional parameters of monopile induced scour should also be included during the development of equations. These parameters are the geometry of monopile, incoming flow, size of sediment, seabed condition and water depth.

5.3. Development of scour prediction models

The phenomena of flow passing through the MCT and MCT induced scour can be investigated by using physical model, analytical method and numerical method. Computational fluid dynamic (CFD) is getting popular due to its reduction of the cost and time in the simulation process. CFD can be used to simulate a full scale structure virtually without consideration of the scaling effect [56].

Deltares, Wallingford and DHI developed a number of scour models in operation. These models took into account the constantly changing hydrodynamics. Deltares is now implementing the software "OSCAR" for scour assessment in the tender phase. This software is based on the empirical–mathematical relations. On the other hand, Deltares developed a flexible integrated modelling feature called Delft3D. This modelling feature has a non-hydrostatic option linked to a Z-model approach. It has been successfully implemented in the process of sediment transport. Delft3D-FLOW is now applicable for a wide range of scour problems around the offshore structures [57]. A combination of physical scale model and CFD model is being used today in Deltares' operation if the detailed or optimised design is required [58].

Nielsen and Hansen [59] from DHI Water and Environment developed an engineering model named WiTuS (Wind Turbine Scour). Their model took into account both the constantly changing hydrodynamics and seabed material properties. The simulation results showed that the scour depth will be approximately 0.3 times of pile diameter for the condition of a larger wave period in North Sea. It is significantly smaller than 1.3 times of pile diameter, which is the industry standard. It demonstrated that larger wave period decreases the scour depth significantly in a combined wave-current condition.

Nielsen's colleagues Dixen et al. [60] developed tables of scour rate to predict long time span of scour around the foundation of offshore wind farm. Dixen's method can be used to predict the scour development at different stages. The tables of scour rate were developed based on the results from 3D simulations. The development of scour hole with times can be predicted as the flow characteristics at different times are known. The predicted results are in good agreement with the experimental data. The new method can also be used to estimate the backfilling of a scour hole for any given structure [60,61].

Dixen et al. [62] recently carried out the numerical and experimental studies of scour on a half-buried sphere by using the steady current flow. The CFD model used in their study was coupled to a morphologic model to calculate scour around the sphere in currents. Dixen et al. [62] concluded that the scour depth is inversely proportional to the turbulent time scale through the CFD investigation. The external generated effect horseshoe-vortex and lee-wake processes are also included in their study. DHI Water and Environment developed the software packages of MIKE 21 and MIKE 3. These packages can also be used to simulate the sediment transport and morphological process for both the non-cohesive and cohesive sediments [63]. The packages are considered as one of the most reliable models for the studies of sediment transport and morphology [64].

These aforementioned numerical models may able to be used to predict MCT induced scour. No particular scour model is available to predict scour of MCT to date. Tidal Bladed from GL Garrad Hassan applied the wind turbine features for the design of tidal turbine. However, the prediction of scour for a tidal turbine has not been found in Tidal Bladed [65]. The inclusion of scour feature in Tidal Bladed may be a useful function to develop the marine current energy.

Scour protection unit has not been used in the MCT in Strangford Loch in 2008. Scour protection has been applied in some of the offshore wind farm in Denmark and Netherlands. The scour protection should also be applied for the MCT. The scour protection unit may also be vulnerable to the scouring process during operational stage. The scour protections can be unstable due to their edges being scoured. This issue has drawn attention from researchers. Nielsen et al. [66–68] proposed the investigation of the scour at protection unit by using the computational models. Nielsen [68] found that numerical model provide valuable information for scour prediction and scour protection design. Numerical simulation can also be a promising method to study the scour pattern around monopile structures of MCT.

Marine soil consists of various layers and the understanding of multi-modal sediment distribution is important for scour prediction [69]. Porter et al. [70] conducted a flume study recently to understand the scour development of layered sediments. The materials of different diameters were used to form the layered bed. The scour development is measured by using both an echo sounder and the photogrammetry technique. The photogrammetry is a non-intrusive approach to obtain the full spatial coordinates of an object. Porter et al. [70] found that the seabed with the coarse sand overlaid by fine sand is more vulnerable to scour compared to the bed with uniform coarse sand. Furthermore, Porter et al. [71] demonstrated that the ratio of equilibrium scour depth to time was significantly changed in the mixed sediment case. The scour models for MCT should consider the layered soil in future research if the potential MCT sites are with mixed sediments.

6. Conclusion

The scour around the support structure of MCT is still poorly understood compared to scour around other marine structures to date. No equation or computational model is available to be used for the prediction of scour depth around the support structures of MCT. In this paper, the appropriate methods have been suggested to predict the scour depth around a MCT. The equations in Section 5.2 have great potential for the scour prediction of the MCT. No objective measure is available to justify the accuracy of the equations for MCT scour prediction. The equations can be used as a foundation to develop engineering models for prediction of MCT induced scour. Further validation is recommended for the appropriateness of suggested equations. The main parameters of MCT induced scour are the diameter of monopile, characteristics of incoming flow, material of bed sediment, influence of rotor and its wake effect. The effects of rotor on the scour depth are the main considerations for studies of MCT induced scour. Future research should focus on the influences of rotor to the scour around MCT. The clearance between the rotor and bed is critical, which may cause the suppression of the adjacent fluid flow at the seabed.

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Appendix A. Correction factor for pier nose shape (K_s)

Shape of pier nose	K_s
(a) Square nose	1.1
(b) Round nose	1.0
(c) Circular cylinder	1.0
(d) Group of cylinders	1.0
(e) Sharp nose	0.9

Appendix B. The correction factor for flow angle of attack (K_θ)

Angle	$L/a=4$	$L/a=8$	$L/a=12$
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.75	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

Angle = Skew angle of flow, L = length of pier (m), a = width/diameter of pier (m).

Appendix C. The correction factor for bed condition (K_b)

Bed condition	Dune height m	K_b
Clear-water scour	N/A	1.1
Plane bed and antidune flow	N/A	1.1
Small dunes	$3>H\geq0.6$	1.1
Medium dunes	$9>H\geq3$	1.2 to 1.1
Large dunes	$H\geq9$	1.3

Appendix D. Correction factor of bed sediment size (K_a)

$d_{50}<2$ mm or $d_{95}<20$ mm	$K_a=1.0$
$d_{50}\geq2$ mm or $d_{95}\geq20$ mm	$K_a=0.4U_*^{0.15}$

$U_*=\frac{U-U_{ic,d_{50}}}{U-U_{ic,d_{95}}}>0$, $U_{ic,d_{50}}=0.645\left(\frac{d_{50}}{D}\right)^{0.053}U_{c,d_{50}}$,

$U_{ic,d_{50}}=K_u h^{1/6} d_{50}^{1/3}$

U_{ic},d_{50} is the approach current velocity required to initiate scour for the grain size d_{50}

U_c,d_{50} is the critical current velocity for incipient motion for the grain size d_{50}

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